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SIMULATING WATERSHED MANAGEMENT PRACTICES ON WOLF CREEK SAN JUAN NATIONAL FOREST

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Simulating Watershed Management Practices on Wolf Creek San Juan National Forest

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Simulating Watershed Management Practices on Wolf Creek San Juan National Forest

INTRODUCTION

Watershed management research during the past 50 years has shown that subalpine forests exert a significant effect on water yields. Changes in the subalpine environment caused by watershed management practices, including successful weather modification and timber harvesting, will affect the water resource. When timber is harvested, the magnitude of hydrologic change will depend on the change in canopy density and the logging method used.

Water is a primary resource in the subalpine zone of the Rocky Mountain Region. Therefore, the need for a planning tool to evaluate potential hydrologic effects of various timber harvesting strategies is obvious in view of the Forest Service goal of sound multiple use management.

This report describes application of a hydrologic systems model to determine the probable effects of timber harvesting and weather modification on Wolf Creek, a 14-square-mile drainage basin northeast of Pagosa Springs, Colorado, in the San Juan National Forest.

The model was developed by synthesizing the technical information presently known about separate components of subalpine hydrologic systems, including snowpack accumulation, melt, and water budgets. It is designed to simulate timber harvesting practices and their resultant effects on hydrologic behavior. We believe that the analysis described in this report is an example of one way that research results can be incorporated into operational resource management.

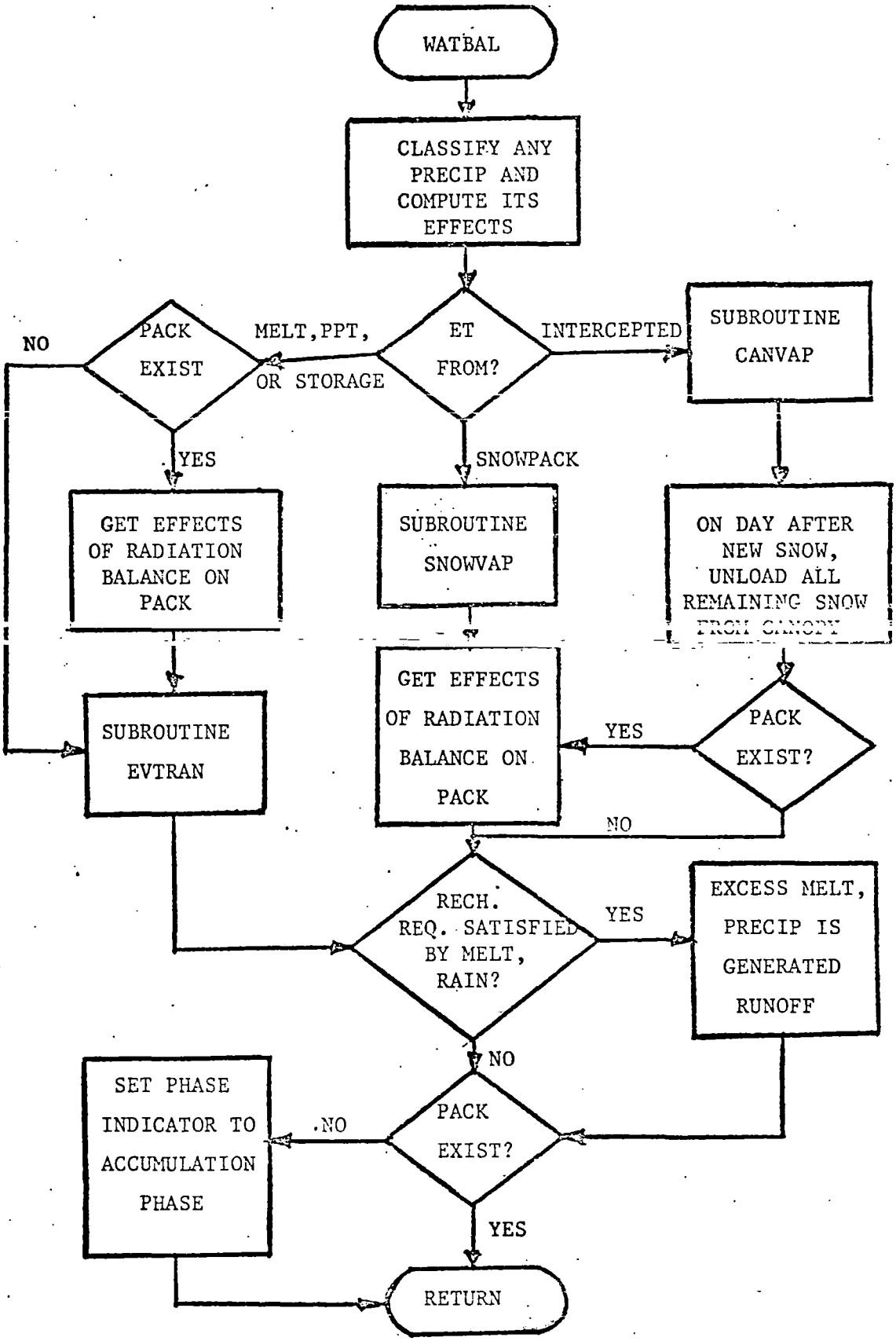
SUBALPINE HYDROLOGIC MODEL

Scope.--Leaf and Brink (1972a, b, c, 1973) have developed a comprehensive hydrologic model which simulates the water balance in several [hydrologic] subunits within a subalpine watershed on a continuous year-round basis, and compiles the results from up to 25 subunits into a "composite overview" of the entire drainage area. The model has been specifically designed to simulate watershed management practices and their resultant effects on hydrologic system behavior.

The discussion which follows is intended to give the reader a general idea of the scope of the model. Detailed flow chart descriptions and more complete hydrologic theory are presented by Leaf and Brink, who have calibrated the model with more than 25 years of field data collected from subalpine watersheds in the Fraser Experimental Forest. A general flow chart of the system is shown in figure 1.

Snowmelt.--Previous work in subalpine forests has shown that radiation is the major source of energy for snowmelt. Accordingly, short- and longwave radiation represent the energy components available for snowmelt. Shortwave radiation to the snow or ground surface beneath the forest canopy is controlled by a transmissivity coefficient which varies according to forest cover characteristics. The incident shortwave radiation as measured on a horizontal surface is adjusted according to the slope and aspect of each hydrologic subunit. Longwave radiation is computed by the Stefan-Boltzmann equation.

Figure 1.--Flow chart of dynamic model which simulates subalpine hydrology.



Snowpack reflectivity is varied according to precipitation form, air temperature, and the energy balance. During the winter months, temperatures within the snow cover are simulated using unsteady heat flow theory. The snowpack will yield melt water only when it has become isothermal at 0° C., and its free water holding capacity is reached.

Interception and Evapotranspiration.--A "potential" evapotranspiration function was developed for the model based on the empirical Hamon equation (Hamon 1961), which requires latitude, converted to day length; and mean monthly temperature, converted to saturation vapor density. The coefficient, C, in Hamon's equation was adjusted upward in order to obtain an expression for potential evapotranspiration under "unlimited" solar input, assumed herein as potential radiation. The evapotranspiration computed by this expression is reduced in proportion to the radiation actually received each day. The adjusted evapotranspiration is then redefined according to its source, which can include:

(1) evaporation from snow intercepted by the forest canopy;

(2) evaporation from the snowpack surface; and (3) evapotranspiration during the growing season.

In developing the interception portion of the model, it was assumed that:

1. The amount of snow intercepted varies according to forest cover type and density;
2. The intercepted snow rests on the canopy for only 1 day following the day of the snow event due to turbulent winds which remove snow from the crowns; and
3. The residual intercepted snow which is not vaporized after that period of time is added to the snowpack.

If the source is evapotranspiration, further adjustments are made to account for: (1) available soil water in open or forested areas, and (2) the reflectivity of open or forested areas.

Input to the watershed system is derived from snowmelt and rainfall. Once evapotranspiration requirements have been satisfied, any remaining input is used to satisfy soil mantle recharge requirements. When "field capacity" is reached, the residual input becomes water available for streamflow (generated runoff).

Hydrologic Subdivisions.--A given subalpine watershed system can be subdivided into as many as 25 hydrologic response units. Divisions vary according to elevation, slope, aspect, and vegetation composition and density. The model is designed to output results from individual subdivisions or compute area-weighted averages to get an over-all response for the entire basin. In this way, both time and spatial variations are realistically accounted for.

WOLF CREEK DRAINAGE BASIN

A location map for Wolf Creek is shown in figure 2. Elevations vary from 8,000 ft. m.s.l. to 12,400 ft. m.s.l. Virtually all of the forest cover is spruce-fir. Figures 3 and 4 are maps that show major topographic features and forest cover. (It should be noted that the areas enclosed by dotted lines are clearcut blocks presently on the north slope.) The area-elevation relationship is shown in table 1.

Hydrologic Subdivisions.--Wolf Creek was divided into 11 subdivisions as seen in figure 4. Further division of forest and open areas resulted in 20 response units used for the simulation analysis. The pertinent geographic characteristics of each response unit are summarized in table 2.

Temperatures.--Daily temperature extremes in each of the 20 response units were estimated by extrapolating observed temperatures at the base station, Wolfe Creek Pass 1E. The equations used were those developed from correlation analyses of temperatures at the Fraser Experimental Forest in central Colorado. Table 3 summarizes the coefficients used in the prediction equations.

Solar Radiation.--Because reliable long-term radiation data are not available in the Wolf Creek area, the shortwave radiation input to the model was generated from potential solar beam radiation as a function of temperature and the slope/aspect characteristics of a given response unit. In order to compute an index of the radiation received, the model adjusts potential radiation downward by means

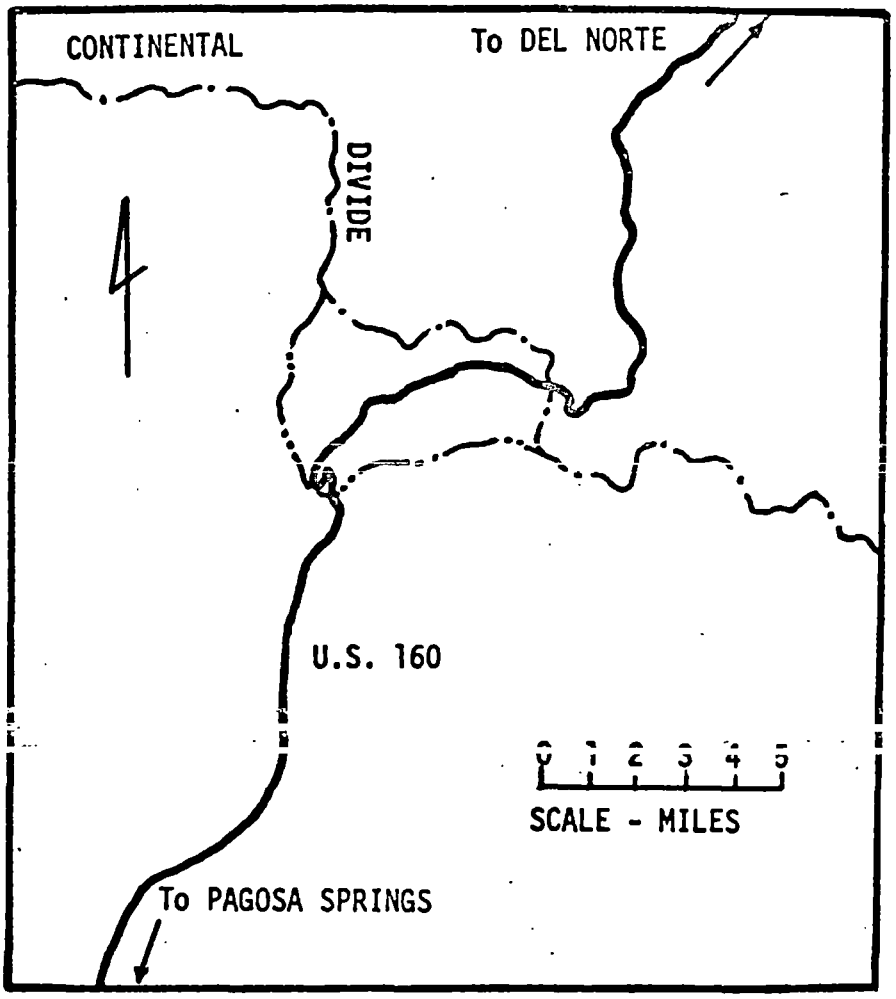


Figure 2.--Location map for Wolf Creek drainage basin.

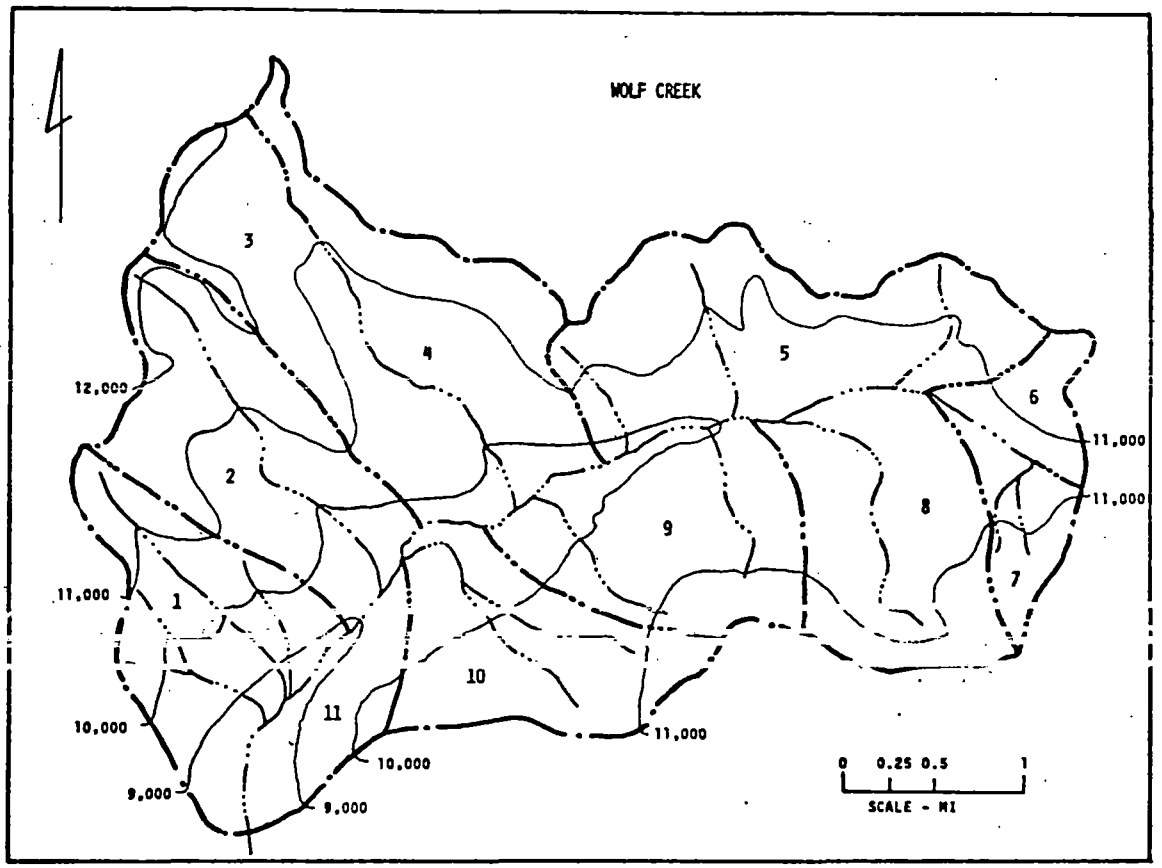


Figure 3.--Wolf Creek drainage basin.

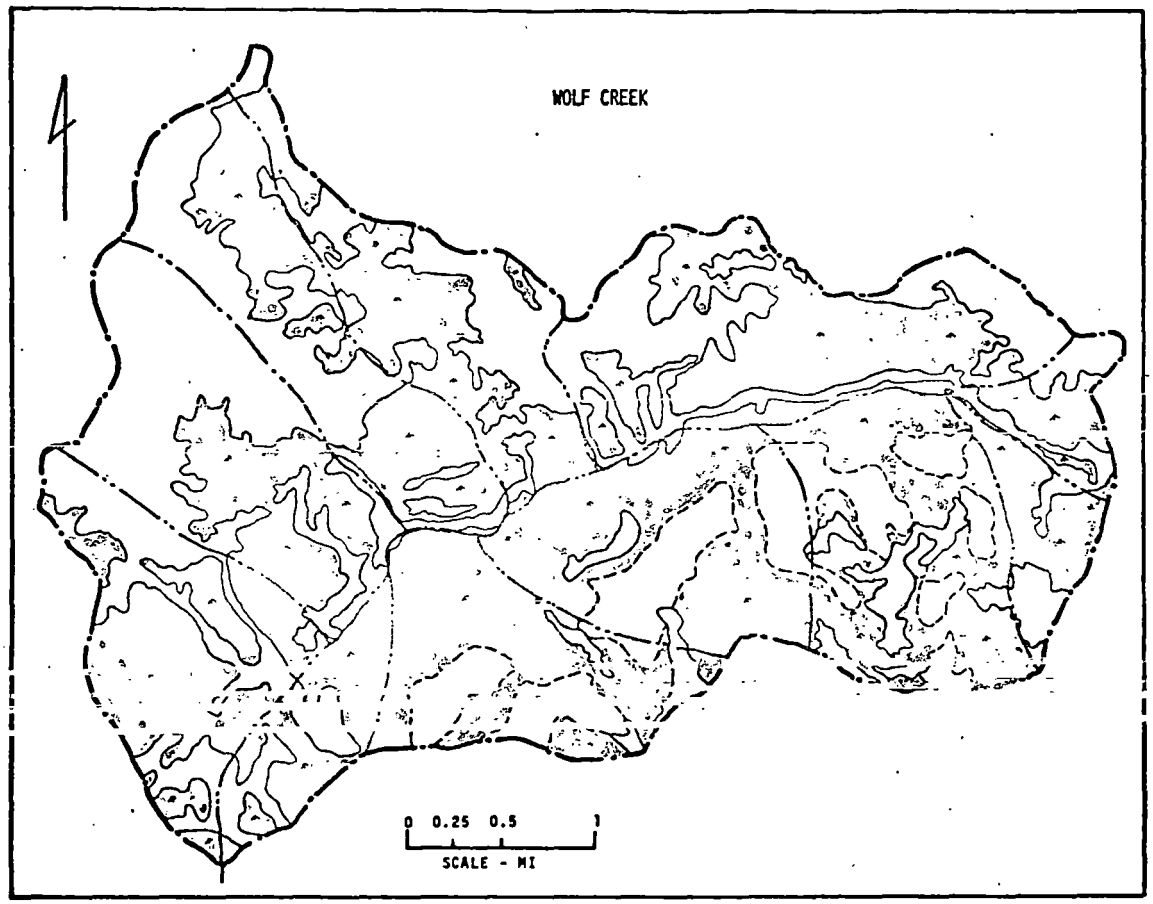


Figure 4.--Extent of forest cover on Wolf Creek. (Areas enclosed by dotted lines are clearcut blocks.)

Exhibit 1/

WOLF CREEK

Area-Elevation Relationships

Elevation Bands	Area in Band (sq. mi.)	% of total area	% area above:		% area above: even percents	
<8,500	0.1	0.5	7,900'	100.0	7,900'	100.0
8,500-9,000	.4	2.8	8,500	99.5	9,630	90.0
9,000-9,500	.6	3.9	9,000	96.7	10,050	80.0
9,500-10,000	1.5	10.8	9,500	92.8	10,290	70.0
10,000-10,500	2.9	20.5	10,000	82.0	10,525	60.0
10,500-11,000	3.7	27.1	10,500	61.4	10,710	50.0
11,000-11,500	3.2	22.7	11,000	34.4	10,900	40.0
11,500-12,000	1.4	10.1	11,500	11.7	11,100	30.0
>12,000	.2	1.6	12,000	1.6	11,320	20.0
					11,590	10.0
					12,390	0

Tabel 2

Geographic Description of Wolf Creek Drainage Basin

Sub-unit	Area (sq. mi.)	Percent total area	Response unit (Ru)	Percent sub-unit	Percent basin	Average elevation	Average aspect	Average slope (%)	Average stocking 2/
1	1.4	10.3	1FW-0	64.5	6.6	10,000	SE	40	MP-MM
			1ØW-0	35.5	3.7	10,500	SE	40	0
2	1.8	12.6	2FW-0	35.4	4.5	10,000	SE	30	MP-MM
			2ØW-0	64.6	8.1	11,500	SE	40	0
3	1.5	11.0	3FW-121	51.3	5.6	10,750	E	20	MP-MM
			3ØW-121	48.7	5.4	11,500	E	40	0
4	1.4	9.8	4FW-160	54.6	5.4	10,750	S	20	MP
			4ØW-160	45.5	4.4	11,000	SW	45	0
5	2.1	14.8	5FW-192	56.2	8.3	10,750	S	35	MP
			5ØW-192	43.8	6.5	11,250	S	40	0
6	0.4	2.6	6FW-196	50.0	1.3	11,100	SW	30	MP
			6ØW-196	50.0	1.3	11,100	SW	20	0
7	0.4	3.1	7FW-9	73.4	2.3	10,900	N	15	MM
			7ØW-9	26.6	0.8	11,000	N	15	0
8	1.6	11.2	8FW-9	86.0	9.7	10,750	N	10	MP-MM
			8ØW-9	14.0	1.5	11,000	N	10	0
9	1.5	10.8	9FW-45	100.0	10.8	10,500	NW	20	MM
10	1.3	9.5	10FW-45	100.0	9.5	10,000	NW	15	MM
11	0.6	4.3	11FW-76	68.6	2.9	9,250	NW	45	MM
			11ØW-76	31.4	1.4	9,000	W	50	0
Sum	14.0	100.0			100.0				

2/ From U.S.F.S. Forest Type Maps:
For MP-MM and MM, $C_D = 65$; $T = 25$
For MP, $C_D = 55$; $T = 25$

Exhibit 9

WOLF CREEK

Air Temperature Correlations
(Base Station is Wolf Creek Pass IE)

Minimum FOR	= A + B*MIN$_{IE}$		Maximum FOR	= A + B*MAX$_{IE}$	
1FW-0	5.025	0.948	1FW-0	7.166	1.028
1ØW-0	5.025	0.948	1ØW-0	7.166	1.028
2FW-0	5.025	0.948	2FW-0	7.166	1.028
2ØW-0	5.025	0.948	2ØW-0	7.166	1.028
3FW-121	-11.993	1.359	3FW-121	-8.995	1.217
3ØW-121	-11.993	1.359	3ØW-121	-8.995	1.217
4FW-160	1.200	0.975	4FW-160	8.545	0.917
4ØW-160	1.200	0.975	4ØW-160	8.545	0.917
5FW-192	0.698	1.023	5FW-192	8.660	0.984
5ØW-192	0.698	1.023	5ØW-192	8.660	0.984
6FW-192	0.698	1.023	6FW-192	8.660	0.984
6ØW-192	0.698	1.023	6ØW-192	8.660	0.984
7FW-9	-0.227	1.004	7FW-9	-1.163	0.961
7ØW-9	-0.227	1.004	7ØW-9	-1.163	0.961
8FW-9	-0.227	1.004	8FW-9	-1.163	0.961
8ØW-9	-0.227	1.004	8ØW-9	-1.163	0.961
9FW-45	2.436	1.105	9FW-45	-1.052	1.058
10FW-45	2.436	1.105	10FW-45	-1.052	1.058
11FW-76	4.770	0.962	11FW-76	1.724	0.981
11ØW-76	4.770	0.962	11ØW-76	1.724	0.981

of a thermal factor. This factor is determined by degree-day relationships which vary according to the season of the year. Table 4 summarizes the coefficients used to adjust potential radiation values for 38° N Latitude to the slope and aspect of each response unit. As stated previously, these values were further adjusted by a thermal factor to get an index of incident shortwave radiation each day.

Precipitation.--Peak snowpack accumulation on Wolf Creek during each of the 11 years simulated is summarized in table 5. These values were estimated from analyses of snowcourse and precipitation transect data obtained from the Soil Conservation Service and Western Scientific Services, Inc., Fort Collins, Colo. (table 1, appendix). To ensure the proper snowpack accumulation as determined in table 5, the base station daily precipitation (at Wolf Creek Pass 1E) was adjusted until the specified peak water equivalent on each response unit was reached.

WOLF CREEK

Potential Radiation; Slope/Aspect adjustments

Response Unit

Date	Pot. Rad. 38°N (cal.)	1FW-0 1ØW-0 2ØW-0 4ØW-160	2FW-0 6FW-192	3FW-121	3ØW-121	4FW-160	5FW-192	5ØW-192	6ØW-192	7FW-9 7ØW-9 8FW-9 8ØW-9	10FW-45	9FW-45	11FW-76	11ØW-76
Jan 10	384	1.58	1.46	1.01	1.02	1.46	1.66	1.84	1.32	0.76	0.83	0.68	0.44	1.03
23	425	1.50	1.40	1.01	1.02	1.40	1.57	1.72	1.28	0.78	0.85	0.71	0.49	1.02
Feb 7	485	1.42	1.33	1.00	1.01	1.33	1.43	1.60	1.24	0.82	0.87	0.76	0.56	1.01
20	558	1.33	1.26	1.00	1.00	1.26	1.37	1.47	1.19	0.85	0.90	0.80	0.62	1.00
Mar 7	639	1.24	1.20	1.00	0.99	1.20	1.23	1.34	1.14	0.88	0.92	0.84	0.69	0.99
21	723	1.17	1.14	1.00	0.99	1.15	1.20	1.24	1.10	0.91	0.94	0.87	0.75	0.98
Apr 4	802	1.11	1.10	0.99	0.98	1.10	1.13	1.15	1.07	0.94	0.95	0.90	0.80	0.97
19	872	1.06	1.06	0.99	0.98	1.06	1.07	1.08	1.04	0.96	0.97	0.93	0.84	0.97
May 3	930	1.02	1.02	0.99	0.97	1.03	1.03	1.02	1.02	0.97	0.98	0.95	0.88	0.96
18	974	0.99	1.00	0.99	0.97	1.00	0.99	0.98	1.00	0.99	0.99	0.97	0.91	0.96
June 1	1004	0.97	0.98	0.99	0.97	0.99	0.97	0.95	0.99	0.99	0.99	0.98	0.93	0.95
22	1021	0.96	0.97	0.99	0.97	0.98	0.96	0.93	0.99	1.00	1.00	0.98	0.94	0.95
Jul 12	1004	0.97	0.98	0.99	0.97	0.99	0.97	0.95	0.99	0.99	0.99	0.98	0.93	0.95
27	974	0.99	1.00	0.99	0.97	1.00	0.99	0.98	1.00	0.99	0.99	0.97	0.91	0.96
Aug 10	930	1.02	1.02	0.99	0.97	1.03	1.03	1.02	1.02	0.97	0.98	0.95	0.88	0.96
25	872	1.06	1.06	0.99	0.98	1.06	1.07	1.08	1.04	0.96	0.97	0.93	0.84	0.97
Sept 9	802	1.11	1.10	0.99	0.98	1.10	1.13	1.15	1.07	0.94	0.95	0.90	0.80	0.97
23	723	1.17	1.14	1.00	0.99	1.15	1.20	1.24	1.10	0.91	0.94	0.87	0.75	0.98
Oct 8	639	1.24	1.20	1.00	0.99	1.20	1.28	1.34	1.14	0.88	0.92	0.84	0.69	0.99
22	558	1.33	1.26	1.00	1.00	1.26	1.37	1.47	1.19	0.85	0.90	0.80	0.62	1.00
Nov 5	485	1.42	1.33	1.00	1.01	1.33	1.43	1.60	1.24	0.82	0.87	0.76	0.56	1.01
19	425	1.50	1.40	1.01	1.02	1.40	1.57	1.72	1.28	0.78	0.85	0.71	0.49	1.02
Dec 3	384	1.58	1.46	1.01	1.02	1.46	1.66	1.84	1.32	0.76	0.83	0.68	0.44	1.03
22	359	1.63	1.50	1.01	1.03	1.50	1.72	1.91	1.35	0.74	0.82	0.66	0.41	1.04

WOLF CREEK

Peak Snow Accumulation or Response Units

Ave. Elev. of response units	Percent area	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
>10,000'	95.7	39.0	24.3	14.2	25.3	18.[illegible]	30.5	16.7	19.7	41.1	26.9	23.3
9,250	2.9	37.4	23.2	13.6	24.2	17.[illegible]	29.3	16.0	18.9	39.3	25.7	22.3
9,000	1.4	33.5	21.7	12.7	22.6	15.[illegible]	27.3	14.9	17.6	36.7	24.0	20.8
Weighted Ave.		38.9	24.2	14.2	25.2	13.[illegible]	30.4	16.7	19.6	41.0	26.8	23.2

		1968	1969	1970	1971	1972
>10,000'	95.7	24.5	32.7	19.1	18.1	19.[illegible]
9,250	2.9	23.4	31.3	18.2	17.4	18.9
9,000	1.4	21.8	29.2	17.0	16.2	17.[illegible]
Weighted Ave.		24.4	32.6	19.0	18.1	19.[illegible]

SYSTEMS ANALYSIS OF WATERSHED MANAGEMENT PRACTICES

The major worth of dynamic models lies in their ability to precisely predict system response from changes in one or several system components. We have used this approach to study the effects of assumed watershed management practices on Wolf Creek, using our best information from field studies and the model described above. All assumptions and analytical procedures used were similar to those discussed by Leaf and Brink (1972 b,c).

Estimated Hydrologic Changes Resulting from Existing Clearcut Blocks.--The north slopes of Wolf Creek have been clearcut in blocks as shown in figure 1. These clearcuts occupy approximately 950 acres. In order to simulate the probable hydrologic effects of the timber harvest, it was assumed that total snow storage in the cutover areas was not changed. Actually, snow accumulation may have been decreased, since there is virtually no wind protection in the large open areas. Moreover, several of the clearcut blocks extend over the ridge and into the adjacent basin.

The results of this simulation are summarized in table 6. The simulated average runoff increase for the 1958-71 record period was 0.6 inch, which resulted from a 0.6-inch decrease in evapotranspiration. Soil water recharge requirements in the fall were decreased by 0.2 inch.

Table 6.--Simulated Hydrologic Changes Resulting from Existing Clearcut Blocks in Sub Areas 8, 9, and 10

Wolf Creek, San Juan National Forest

Response Unit: Total Watershed

Component	Water balance, in inches		
	Natural	Treated	Change
Precipitation	48.2	48.2	0
Evapotranspiration	20.5	19.9	-0.6
Recharge requirement			
beginning (10/1)	2.9	2.7	-0.2
end (9/30)	2.9	2.7	-0.2
Water yield	26.6	27.2	+0.6

Patch-cutting.--Research in the Rocky Mountain Region has shown that patch-cutting subalpine forests results in significant redistribution of the winter snowpack. When openings are: (1) less than at least 5 but 8 tree-heights in diameter; (2) protected from wind; and (3) interspersed so that they are 5 to 8 tree-heights apart, an optimum pattern of snow accumulation results. More snow is deposited in the openings, and less snow accumulates in the uncut forest so that total snow storage on headwater basins is not significantly increased. Moreover, the combined action of redistribution and reduced evapotranspiration results in a water yield increase of 15 to 25 percent. Patch-cutting small openings results in accelerated snowmelt early in the melt season and diminished snowmelt later. Thus, streamflow on the rising limb of the hydrograph is higher, and peak flows may be slightly increased. If there is sufficient natural regulation in the form of deep porous soils, recession flows are not changed after the timber on 40 to 50 percent of the watershed is removed in a system of small openings.

Another important point is that patch-cutting in 5 to 8 H openings is silviculturally sound and compatible with guidelines recently developed from research in old-growth lodgepole pine and spruce-fir. This type of management would preserve the natural landscape by maintaining a high forest cover in areas where recreation and aesthetics are important.

Table 7 summarizes simulated hydrologic changes resulting from patch-cutting 40 percent of the area of sub areas 7-11 (assuming that the present blocks were not cut). It is seen that this system would have produced at least as much increased water yield as the large clearcut blocks. In all probability, the increase would have been higher, since snow accumulation in the large openings may [not] be less than before the timber harvest.

Water Yield Increases on North and South Slopes.--In the foregoing analysis, hydrologic changes were predicted for the entire watershed. Because research has shown that hydrologic regimes of sub areas within even small subalpine watersheds can vary by several orders of magnitude, analyses similar to the one shown in table 7 were made on north and south slope response units. Predicted water yield increases from patch-cutting on two of these units were as follows:

Response Unit	Water Yield Increase
South Aspect (2FW-ϕ)	3.6 in.
North Aspect (10FW-45)	2.8 in.

It is important to note that, in their natural states, south slopes are less efficient than north slopes in producing streamflow. At first thought, it would appear that the highest potentials for water yield improvement exist in the protected spruce-fir forests where precipitation is greater and consumptive use is least. However, this is apparently not the case. As seen in the above comparisons, water yield increases are apparently as high or higher than increases from north slopes.

Table 7.--Simulated Hydrologic Changes Resulting from Patch-cutting 40 Percent Area in 5 H Openings in Sub Areas 7, 8, 9. 10, and 11 Wolf Creek, San Juan National Forest

Response Unit: Total Watershed

Component	Water balance, in inches		
	Natural	Treated	Change
Precipitation	48.2	48.2	0
Evapotranspiration	20.5	19.8	-0.7
Recharge requirement			
beginning (10/1)	2.9	2.9	0
end (9/30)	2.9	2.9	0
Water yield	26.6	27.3	+0.7

Selection Cutting.--Table 8 summarizes predicted hydrologic changes when the forest canopy density is uniformly reduced 50 percent in response units 7 through 11 on Wolf Creek. (It was assumed that this option corresponds to removal of at least 40 percent of the timber volume.) A comparison of tables 7 and 8 shows that patch-cutting apparently increases water yields more than selection cutting. In fact, water yields may actually be reduced somewhat if this management option is used. In the selection cutting option, evapotranspiration is increased 0.2 inch, compared to a 0.7-inch decrease for patch-cutting. Figure 5 compares year-by-year changes in water yield resulting from the patch-cut and selection-cut options.

Overall, the effect on snowmelt timing when selection cutting is employed is not large. Snowmelt can be accelerated or delayed when the forest canopy density is reduced, depending upon aspect; however, in no case is the change in timing as large as with patch-cutting.

Water Yield Changes on North and South Slopes.--Predicted water yield changes resulting from a 50 percent forest canopy density reduction on north and south slope response units on Wolf Creek is summarized below:

Response Unit	Change in Water Yield
South Aspect (2FW-ϕ)	-1.2 in.
North Aspect (10FW-45)	-0.3 in.

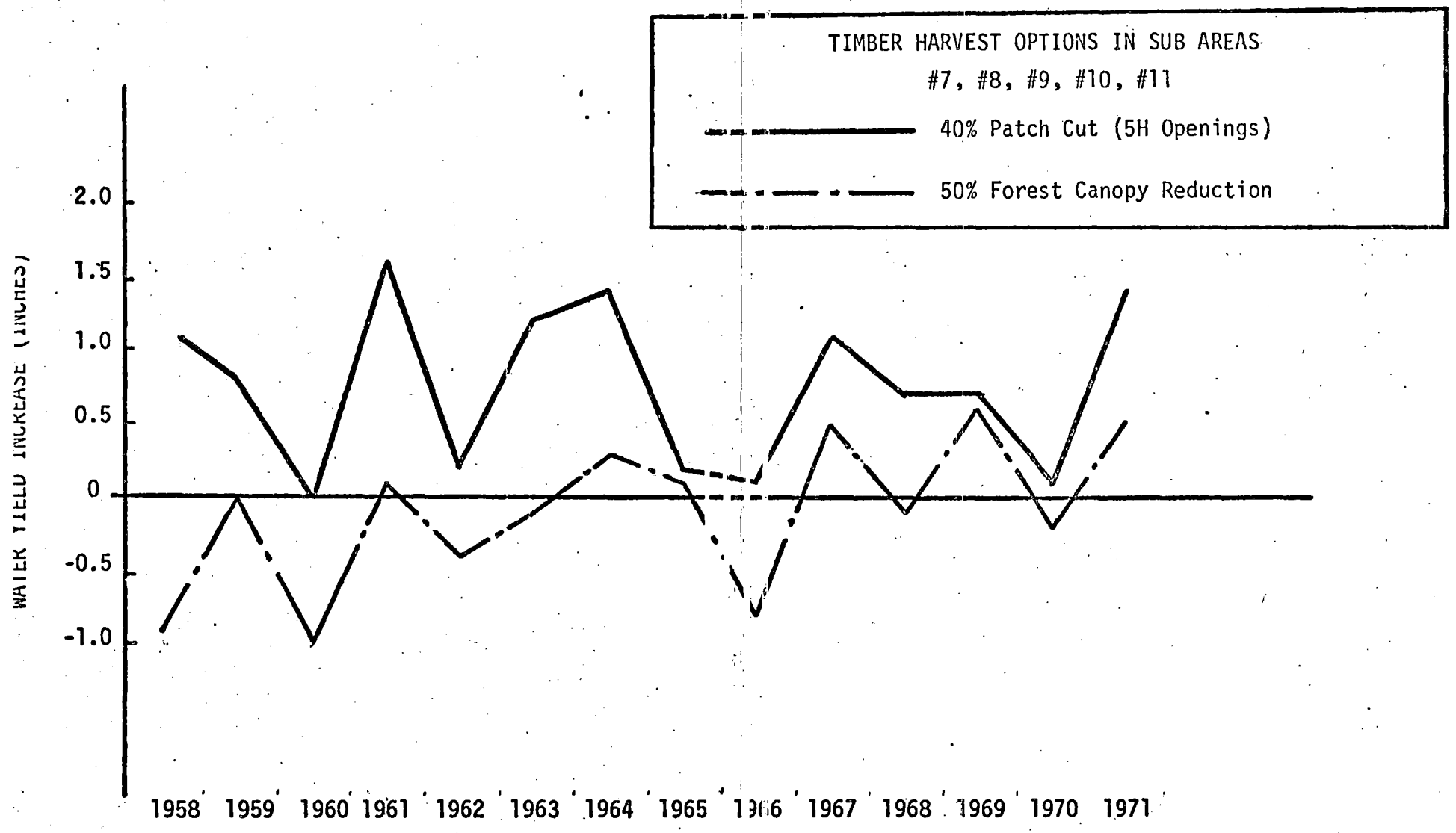
Table 8.--Simulated Hydrologic Changes Resulting from a 50 Percent Reduction in Forest Canopy Density in Sub Areas 7, 8, 9, 10, and Wolf Creek, San Juan National Forest

Response Unit: Total Watershed

Component	Water balance, in inches		
	Natural	Treated	Change
Precipitation	48.2	48.2	0
Evapotranspiration	20.5	20.7	+0.2
Recharge requirement			
beginning (10/1)	2.9	2.4	-0.5
end (9/30)	2.9	2.4	-0.5
Water yield	26.6	26.4	-0.2

SIMULATED WATER YIELD INCREASES RESULTING FROM TIMBER HARVESTING

WOLF CREEK - SAN JUAN NATIONAL FOREST



It is significant to note that uniform canopy reduction apparently results in less water yield on both north and south slope response units; whereas, when the same timber volume is removed in a system of small openings, water yields are increased.

Weather Modification.--Weather modification technology in the Rocky Mountain subalpine zone has evolved to the point where pilot projects are being undertaken for the purpose of increasing water yields. One of the largest of these is the San Juan Pilot Project, currently being sponsored by the Division of Atmospheric Water Resources, Bureau of Reclamation.

Early evidence from seeding experiments on Wolf Creek Pass by Colorado State University indicated that perhaps 20 to 40 percent of the winter storms are favorable for increasing precipitation. It has been estimated that increases affected by seeding during favorable situations in the Wolf Creek area are in the order of 50 to 100 percent. Accordingly, we have made preliminary studies with the Subalpine Water Balance Model to quantify the hydrologic effects of successful weather modification. These studies were based on an assumed 15 percent increase in winter snowfall between November 30 and March 31 of each year.

Table 9 summarizes average results from a 15-year period of record. An average 3.8 inches of increased water equivalent for 1957-71 on Wolf Creek produced an average 3.7 inches of additional water yield with a 0.1-inch increase in evapotranspiration and a 0.2-inch increase in soil water storage. In this case, the increased

Table 9.--Simulated Hydrologic Changes Resulting from a 15 Percent Increase in Snowpack Between November 1 and March 21

Wolf Creek, San Juan National Forest

Response Unit: Total Watershed

Component	Water balance, in inches		
	Natural	Treated	Change
Precipitation	48.3	52.1	+3.8
Evapotranspiration	19.8	19.9	+0.1
Recharge requirement			
beginning (10/1)	2.7	2.5	-0.2
end (9/30)	2.7	2.5	-0.2
Water yield	27.2	30.9	+3.7

Snow accumulation did not extend the duration of the melt season more than 3 to 5 days. More than 95 percent of the increased snowpack produced streamflow. Because water yield benefits result from the last snowmelt at a given location, the bulk of the increased runoff is released during and just after peak streamflow. This would have a tendency to broaden the snowmelt hydrograph and possibly increase both peak and recession flows.

The simulation model has also given some indication as to the degree that successful weather modification would increase the efficiency of vegetation management practices. Under this option, comparisons were made between the natural water balance and the balance resulting from manipulating the model to simultaneously account for: (1) patch-cutting the watershed so that 40 percent is occupied by small openings, of the area in sub units 7 through 11, and (2) increasing the winter snow accumulation by 15 percent. As seen below, the combined effect was to increase the water yield from 3.7 inches when the snowpack was increased under natural conditions to 4.4 inches when coupled with the simulated patch-cuts on the north slope.

Watershed Management Option	Water Yield Increase
15 percent snowpack increase	3.7 in.
Combined patch-cut in units 7-11 and weather modification	4.4 in.

CONCLUSIONS

The purpose of this report has been to show how a dynamic systems model was used to determine the probable hydrologic effects of timber harvesting and weather modification on Wolf Creek. The following paragraphs highlight technical aspects of this work and summarize principles which are important for multiple use management in the San Juan National Forest.

- Patch-cutting subalpine forests results in redistribution of the winter snowpack. When openings are: (1) greater than 5 but less than 8 tree-heights in diameter; (2) protected from wind, and (3) interspersed so that they are 5 to 8 tree heights apart, an optimum pattern of snow accumulation results. More snow is deposited in the openings, and less snow accumulates in the uncut forest so that total snow storage on headwater basins is not significantly increased.
- Snowmelt in cutover areas on all aspects is more rapid than in the uncut forest. This accelerated melt causes streamflow to be higher on the rising limb of the hydrograph than before harvest cutting. Where there is considerable natural regulation in the form of deep porous soils, recession flows are not changed and annual flood peaks are not significantly increased provided that the forest cover on no more than 50 percent of the watershed is removed in a system of small openings.

- Simulation analyses on Wolf Creek indicate that under a patch-cut alternative, water yield increases on south aspects are at least as large as corresponding increases from north aspects. Hence, there is no reason to favor areas having the highest natural water yield if the objective is to maximize water yields from medium to dense old-growth spruce-fir forest.
- Tentative results indicate that highest increases in streamflow result when subalpine forests are harvested in a system of small forest openings. Simulation analyses indicate that, if the forest canopy is reduced a given amount through selection cutting, overall water yield improvement is not attained. When the canopy density is reduced 50 percent in spruce-fir forests, water yields may actually be decreased.
- The timber harvesting measures recommended for maximum water yields are silviculturally sound and compatible with the guidelines recently developed from research in old-growth lodgepole pine and spruce-fir. This type of management would preserve the natural landscape by maintaining a high forest cover in areas where recreation and aesthetics are important.

- Preliminary results from the Subalpine Water Balance Model indicated that on Wolf Creek, a 15 percent increase in snow accumulation through successful weather modification will increase water yields 14 percent in the average year. Weather modification apparently will not extend the snowmelt season more than 3 to 5 days, and apparently does not significantly affect evapotranspiration. Because water yield benefits result from the last snowmelt at a given location, the bulk of the increased runoff is released during and just after peak streamflow. This would have a tendency to broaden the snowmelt hydrograph and possibly increase peak and recession flows. Successful augmentation of natural snowfall will significantly increase the efficiency of vegetation management practices. When 40 percent of a watershed is occupied by 5 H forest openings, increased water yields can almost be doubled if the natural snowpack is increased by 15 percent.

REFERENCES

Leaf, Charles F., and Glen E. Brink.

1972a. Computer simulation of snowmelt within a Colorado subalpine watershed. (In preparation for publication, Rocky Mt. Forest and Range Exp. Stn., USDA Forest Serv., Fort Collins, Colo.)

_____, and Glen E. Brink.

1972b. Simulating effects of harvest cutting on snowmelt in Colorado subalpine forest. In Watershed in Transition Symp. [Fort Collins, Colo., June 1972] Proc. Ser. 14, 405 p. Am. Water Resour. Assoc., Urbana, Ill.

_____, and Glen E. Brink.

1972c. Simulating watershed practices in Colorado subalpine forest. Amer. Soc. Civil Eng. Annual and Nationl. Environmental Eng. Meeting Preprint 1840, 26 p. [Houston, Texas, Oct. 16-20.]

_____, and Glen E. Brink.

1973. Hydrologic model of Colorado subalpine forest. (In preparation for publication, Rocky Mt. Forest and Range Exp. Stn., USDA Forest Serv., Fort Collins, Colo.)

APPENDIX

Table 1.--Normalized Snow Accumulation Data

Wolf Creek[3/]

Year	Date snow survey	Wolf Creek Pass IE	Upper San Juan	Wolf Creek Summit	Site Number LN1 (7,780)	LO1 (7970)	KO2 (8120)	KO3 (9510)	KO4 (9770)	JO1 (10,810)	KP3 (10,660)
		- Snow courses[5/]			Precipitation stations[4/]						
1970	3/30	20.5	21.1	24.7	(9.0)	9.8)	(10.2)	18.8	(17.3)	(16.7)	14.4
1971	2/26	19.5	20.7	20.1	7.3	9.5	10.3	18.6	17.6	15.7	14.5
1972	2/28	21.2	23.5	26.1	11.2	13.4	13.9	23.2	24.2	20.2	20.9

[4/] Precip. adjusted to date of snow survey.
Numbers in (X) were estimated from interstation precipitation ratios for 1970.

Normalized to Wolf Creek Pass IE - elevation 10,000 feet

Year	LN1	KO1	KO2	KO3	KO4	JO1	KP3
1970	.44	.48	.50	.92	.84	.81	.70
1971	.37	.49	.53	.95	.90	.81	.74
1972	.53	.63	.66	1.10	1.14	.95	.99
Mean	0.45	0.53	0.56	0.99	0.96	0.86	0.81

Normalized to Upper San Juan - elevation 10,000 feet

Year	LN1	KO1	KO2	KO3	KO4	JO1	KP3
1970	.43	.46	.48	.89	.82	.79	.68
1971	.35	.46	.50	.90	.85	.76	.70
1972	.48	.57	.59	.99	1.03	.86	.89
Mean	0.42	0.50	0.52	0.93	0.90	0.80	0.76

[3/] Western Scientific Services, Inc., Comprehensive Meteorological Data Reports for 1969, 1970, and 1971. Prepared for: United States Department of Interior, Bureau of Reclamation, Division of Atmospheric Water Resources Management.

[5/] USDA, Soil Conservation Service. Federal-State-Private Cooperative Snow Survey. Water Supply Outlook Reports.